A 3.4–3.6-GHz High Efficiency Gallium Nitride Power Amplifier Using Bandpass Output Matching Network

Qianteng Wu and Xiaoguang Liu
* University of California, Davis, CA, USA, 95616

***Abstract*—This paper presents a high efficiency Gallium Nitride (GaN) class-F power amplifier (PA) which uses a Chebyshev bandpass filter to realize the optimal fundamental and harmonic impedance matching. The bandpass output matching network also absorbs the output parasitics of the power amplifier. A prototype PA is implemented to verify this idea, which delivers output power of 37.5 dBm with peak power added efficiency (PAE) of 78% and gain of 13.5 dB at 3.5 GHz, and PAE above 74% in a 200 MHz bandwidth.**

***Index Terms*—Power amplifiers, GaN, class-F, efficiency.**

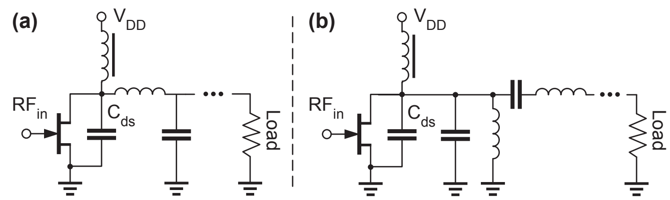

Fig. 1. (a) Lowpass filter based class-F power amplifier. (b) Bandpass filter based class-F power amplifier.

I. INTRODUCTION

Power amplifiers are essential RF component for modern electronic systems. High efficiency power amplifiers can lower the DC power consumption, reduce device heat dissipation and increase battery life [1].

PA operation modes of class-E and class-F/F^{-1} take advantage of output harmonics to construct specific voltage and current waveform to improve the power efficiency. In particular, high efficiency is achieved in class-F PA by creating non-overlapping rectified current and rectangular voltage waveforms by presenting open circuit for odd harmonics and short circuit for even harmonics to the current source of the power transistor [2]. In practice, control of harmonics up to the third has been done [3], which can achieve a theoretical drain efficiency of 90.7% [1].

Conventional design methods of a class-F PA is to use a lowpass output matching network. Fig. 1-a shows a typical typology of such a network. In this paper, we explore the use of a generalized-Chebyshev bandpass filter to implement the output matching network, as show in the Fig. 1-b. For systems that are required to work over a particular bandwidth, a bandpass network may achieve better matching, as dictated by the Bode-Fano criterion. In this work, we will also show that the proposed bandpass matching network can also absorb the output parasitics (primarily C_{DS}) of the power transistor, while creating optimal impedances at the fundamental as well as the harmonics. Following the design methodology, a class-F PA is demonstrated with a 37.5 dBm output power and a peak power added efficiency (PAE) of 78% and at 3.5 GHz.

II. CIRCUIT DESIGN

A 0.25-µm Gallium Nitirde (GaN) HEMT transistor is used in this PA design. This power transistor has a width of 1.2 mm and operates at a drain voltage of 28 V with a saturation current of 550 mA. This transistor exhibits a C_{DS} with weak large-signal dependence. The value of C_{DS} is extracted to be 0.24 pF using the method presented in [4]. The small C_{DS} makes it easier to be incorporated into the output matching networks. The goal of this design is to reach as high of a PAE as possible with an output power greater than 36 dBm at 3.5 GHz.

A. Output Matching Network Design

1) Determination of Load Impedance: The optimal fundamental load impedance of the class-F PA is 4/π larger than that of the class-B PA's. In this design, the optimal class-B load impedance is determined to be 70 Ω by load-pull simulation using a non-linear transistor model in Keysight Advanced Design System (ADS). The corresponding load impedance for the class-F amplifier is therefore set to 90 Ω.

2) Filter Synthesis: We start the output matching network from a simple Chebyshev bandpass filter. A 6th-order filter is chosen as a starting point because: 1) it has enough degrees of freedom to realize impedance matching at both the fundamental and high harmonics; 2) it has lower loss when compared with higher order filters. Fig. 2-a shows the synthesized bandpass filter with reference impedance of 50 Ω at both ports. The bandwidth for the prototype is set to slightly larger than the desired bandwidth (3.1–3.9 GHz) with a passband ripple of 0.1 dB.

3) Impedance Transformation: Norton's transformation is used to transform the input impedance of the synthesized Chebyshev output matching network with the following procedures.

A) Add an ideal transformer to the input port as shown in Fig. 2-b and change the impedance of this port to the desired value of 90 Ω.

B) Exchange the position of the transformer and the first shunt resonator as shown in Fig. 2-c.

C) Apply Norton's transformation and then divide the C_1 into C_{DS} and C_5 as show in Fig. 2-d, which absorbs the C_{DS} into the filter structure.

4) Distributed Implementation and Optimization: In the actual implementation of the output matching network, the shunt and series inductors are replaced by high impedancc lines and the shunt capacitors are replaced by low impedance

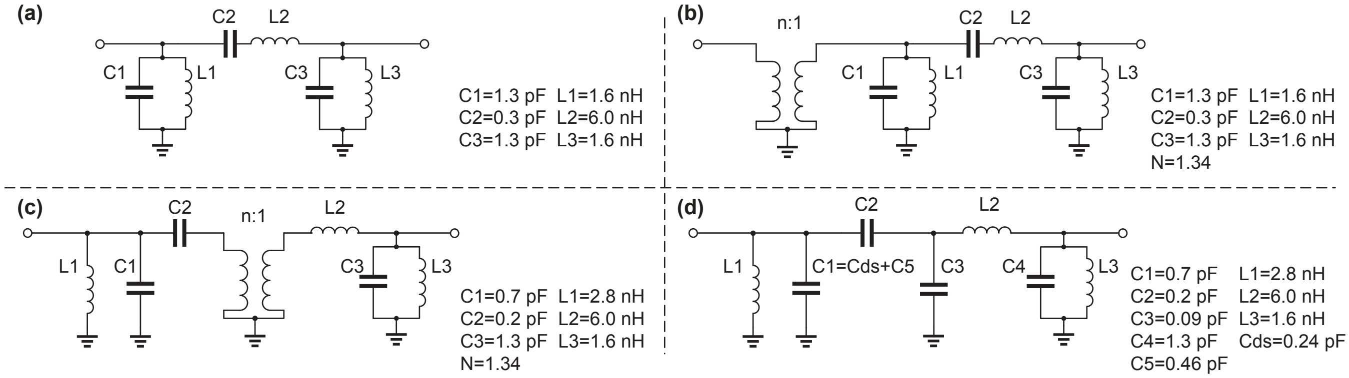

Fig. 2. (a) Three stages synthesized chebyshev bandpass filter. (b) Synthesized chebyshev bandpass filter with left port impedance of 90 Ω. (c) Move transformer to the middle part of the synthesized chebyshev bandpass filter. (d) Synthesized chebyshev bandpass filter after Norton's transform.

open circuit stubs. For the convenience of the implementation, characteristic impedances of these high impedance and low impedance lines are set to 90 Ω and 50 Ω respectively. The implemented filter-based output matching network is optimized by changing of lengths of the transmission lines. From simulation, it can be found that harmonic impedances are very sensitive to the length of TL_{O1} and TL_{O5}. Fig. 3 shows the output matching network after the optimization. Also, because of the very small value of C_3 in Fig. 2-d which has little contribution to the filter response, C_3 is neglected in the final design. By optimizing the lengths of the output transmission lines, the second harmonic could be set to short circuit and third harmonic could be set to open circuit to create the desired class-F current and voltage waveforms. Fig. 4 illustrates the input impedances of the lumped-element network, the distributed-element network before and after optimization.

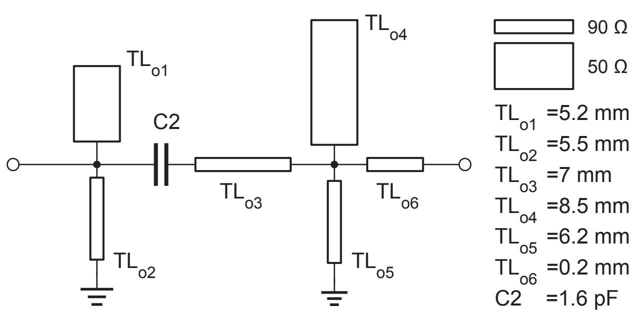

Fig. 3. Output matching network after the optimization.

B. Input Matching Network Design

The input matching network is designed by using the same philosophy as the output matching network, which is implemented by the high impedance and low impedance transmission lines. For the stability concern, a small resistor of 5 Ω in series with a high-impedance line is added at the gate of the GaN HEMT.

Fig. 5-a shows the dimensions of all transmission lines of the final design. The simulated current and voltage waveforms of the de-embedded transistor are shown in Fig. 5 (b),

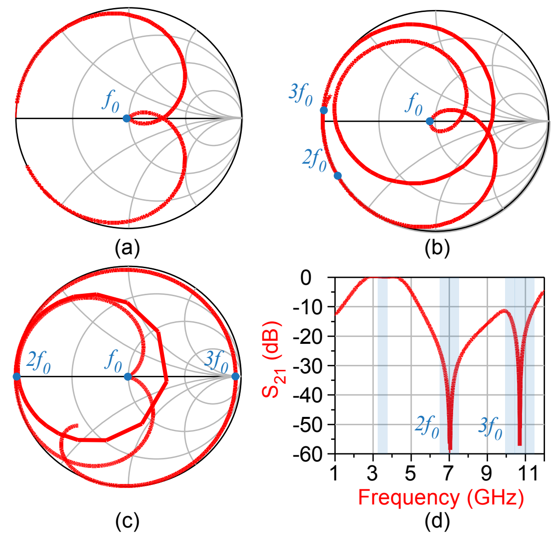

Fig. 4. (a) S_{11} of lumped component network. (b) S_{11} of distributed elements network without optimization. (c) S_{11} of optimized distributed elements network

demonstrating minimal overlap. The simulated output power and PAE are greater than 36 dBm and 65% respectively over 3.3–3.7 GHz.

III. Experimental Results

This class-F PA is fabricated on a 10 mil thick Rogers 5880 high frequency laminate. The GaN HEMT die is attached to a heat-sink through a opening in the substrate and wirebonded to the input and output networks. Fig. 6 shows the fabricated PA design and board dimensions.

The implemented PA is measured from 3.3 GHz to 3.7 GHz. The gate of the transistor is biased at -2.5 V which is a little bit higher than the threshold voltage of the transistor and drain is biased at 28 V. The quiescent current is 26 mA. The measured small-signal S_{21} of the PA is shown in Fig. 7-a. The transmission zeros at the second and third harmonics can be clearly observed. The measured PA's large signal performances are presented in Fig. 7-b&c. The PA achieves an output power of greater than 36 dBm and a PAE higher than 70% over a

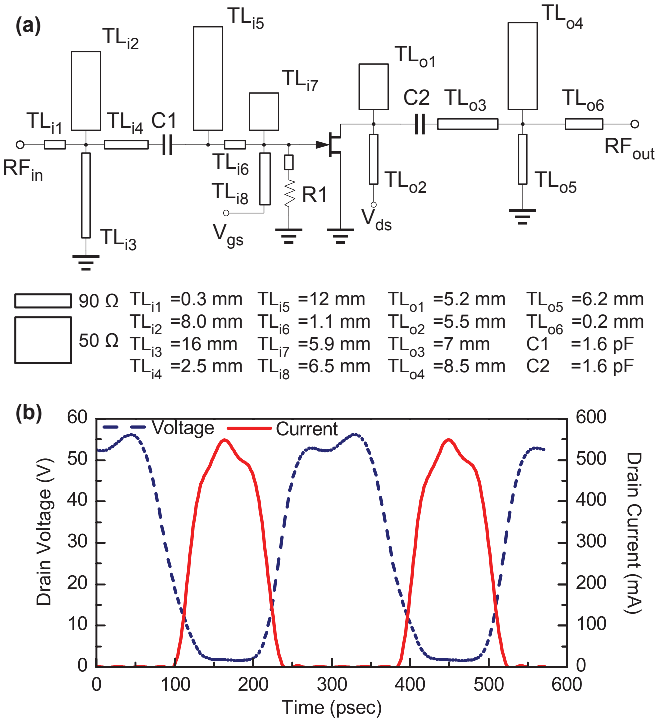

Fig. 5. (a) Optimized schematic of the complete PA; (b) Simulated current and voltage waveforms at the transistor current source.

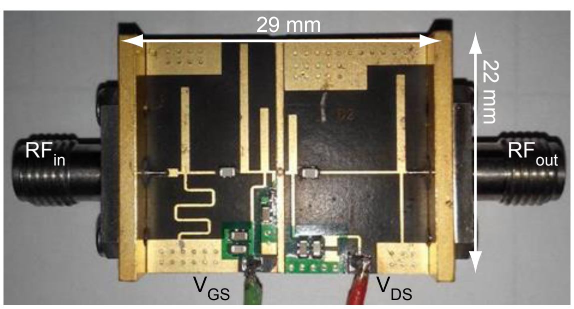

Fig. 6. Picture of the fabricated PA.

bandwidth of over 3.37–3.65 GHz. The measured peak output power and PAE are 37.5 dBm and 78% respectively. The measured results agree very well with the simulation.

IV. Conclusion

A class-F power amplifier design based on a Chebyshev bandpass filter as matching network is presented in this paper. Good matching of both fundamental and harmonics are obtained by using a three stages Chebyshev bandpass filter. A prototype of this class-F PA exhibits the output power of 37.5 dBm with high PAE of 78% at 3.5 GHz, and PAE above 74% in 200 MHz bandwidth, proving the effectiveness of the proposed design approach.

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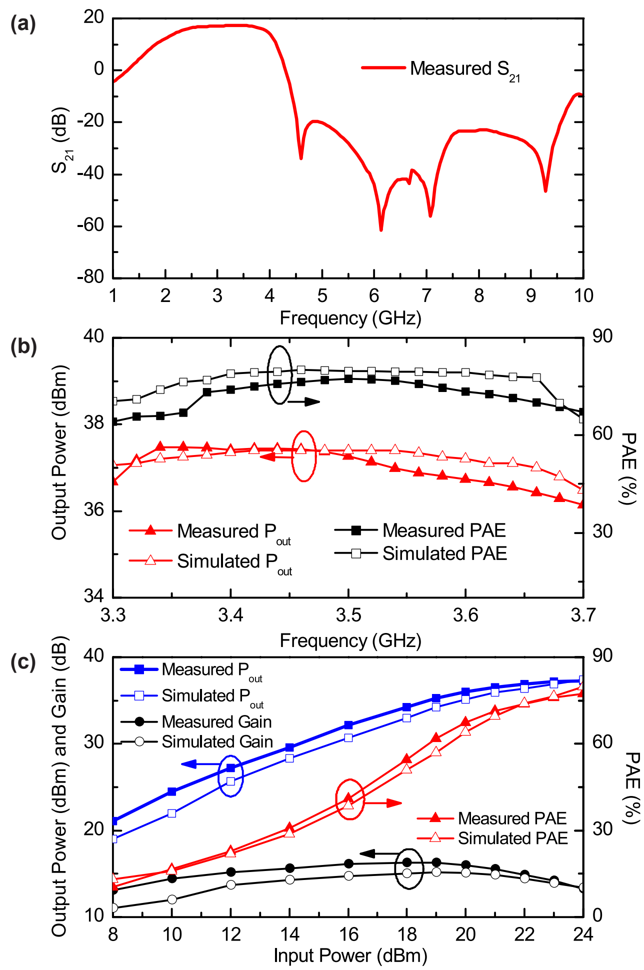

Fig. 7. Measured and simulated PA performances.

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